Human sleep and cortical reactivity are influenced by lunar phase

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Various human biological functions adhere to a circadian rhythm that to some extent may be affected by environmental factors, including light and temperature [1]. Recent evidence from Cajochen *et al*. [2] indicates that human sleep is influenced by the cycle of the moon, measured in conditions precluding the potential impact of nocturnal lunar illumination Here in a similarly retrospective study of 47 healthy volunteers (mean age 23.3, S.D. ±2.9 years) we demonstrate that total sleep time decreases by 25 minutes and cortical reactivity to environmental stimuli during sleep increases around full moon, and rapid eye movement (REM) sleep latency lengthens by 30 minutes around new moon. The findings strengthen the notion that human sleep is modulated by lunar phase but point to important deviations from the study of Cajochen *et al*. that need to be addressed, particularly with regard to individual susceptibility.

We retrospectively analyzed sleep architecture data from young, healthy volunteers in quiet, controlled conditions. The sleep laboratory was constructed and equipped to simulate a residential apartment as much as possible, rather than the clinical settings typically used in such research, in order to ensure high ecological validity and thereby minimize any influence of the environment on measured outcomes. Lunar phase was classified in the same manner as by Cajochen *et al*. into three lunar classes [2] (see Experimental Procedures in Supplemental Information, published with this article online). There were no indications that the number of daylight hours was unevenly distributed between lunar classes (Table S1). Main effects of lunar class were observed for REM latency and total sleep time (Table S2). In accordance with the literature, no effects were observed on wakefulness (WASO) or time in slow wave (SWS, low frequency (0.5 Hz–2 Hz) high amplitude (>75 μV) EEG activity), non-REM or REM sleep. Additionally, no effects were found on total number of sleep stage changes, awakenings or arousals. Cajochen *et al*. found effects on melatonin, electroencephalography (EEG)-delta activity and stage 4 sleep, parameters not measured in the current work.

Further analysis of total sleep time revealed a significant ($p = 0.046$) reduction around full moon of 24.8 minutes relative to quarter moon (Figure 1A). This corresponds very closely to the 24.2 minutes reported previously [2]. The significant interaction between lunar class and gender ($F(2,35) = 5.6$, $p = 0.008$) shows that this effect was driven by males, who slept for 51.1 minutes less than females around full moon, corresponding to reduced sleep efficiency of 10.6% (Figure S1).

Although no main effects of lunar class were observed for sleep onset latency, further analysis revealed a significant interaction with gender ($F(2,35) = 5.6$, $p = 0.008$), showing that unlike females, males take between 35–40.5 minutes longer to fall asleep around full moon than during other phases (Figure 1B). Interactions were also found between gender and lunar class for N1 ($F(2,35) = 6.8$, $p = 0.003$) and N2 sleep ($F(2,35) = 6.6$, $p = 0.004$). Males had increased time in N1 (colloquially known as 'light sleep' and typified by low amplitude, mixed frequency activity in the EEG), corresponding to a reduction in N2 ('intermediate sleep', characterized by the presence of K complexes and sleep spindles) closer to the full moon.

REM latency was longest around new moon (100.6 minutes), approximately 30 minutes longer than at full and quarter moons ($p < 0.01$). This is in contrast to the findings of Cajochen *et al*., who found the longest REM latency at *full* moon (89.3 minutes) with shorter latencies during quarter and new moons. In our studies, we specifically investigated the effects of environmental sensitivity on response and recruited subjects accordingly. Grouping our sample by persons with and without high sensitivity, we found the non-sensitive group was unaffected by moon phase, whereas sensitive persons entered REM 56.5 minutes later around new moon than at full moon (interaction of sensitivity and lunar class $F(2,35) = 4.09$, $p = 0.014$; Figure 1C). Since the effect is attributable to sensitivity, it is plausible that there were insufficient sensitive individuals in the Cajochen *et al*. trials to influence their findings. The significance of REM latency *per se* is difficult to interpret. The first sleep cycle can be defined as the interval between sleep onset latency and cessation of the first REM period, and hence one interpretation is that sleep cycle duration (and subsequent structure) is influenced by lunar phase.

Despite the relatively small study population and subsequently wide confidence intervals, particularly around full moon, we found significant effects of lunar phase on total sleep time and sleep onset latency, with males being more affected than females. This contrasts with previous work using sleep diaries, which suggested that women were more affected according to moon phase, although the interaction in this study was statistically weak [3]. These findings support those reported previously by Cajochen *et al*., although possible gender effects warrant further research. Also in agreement, we found no effect on WASO, SWS, non-REM or REM. Findings that did not support the earlier research were REM latency being shortest around full moon, potentially due to our inclusion of particularly sensitive individuals, and subjective sleep quality for which we found no effect. However, only volunteers with good self-reported sleep in general were recruited and may therefore represent a particularly subjectively resilient group. The presence of objective effects may be reconciled with self-reported measures of sleep not necessarily correlating accurately with physiological response [4]. However, despite the controlled lighting conditions during the sleep period time, it cannot be completely excluded that external conditions prior to arriving at the laboratory (e.g., increased nocturnal illumination around full moon) did not contribute towards measured sleep outcomes.

Our data furthermore allow us to examine the effect of lunar cycle in nights with external stimuli. Four nights following the quiet baseline

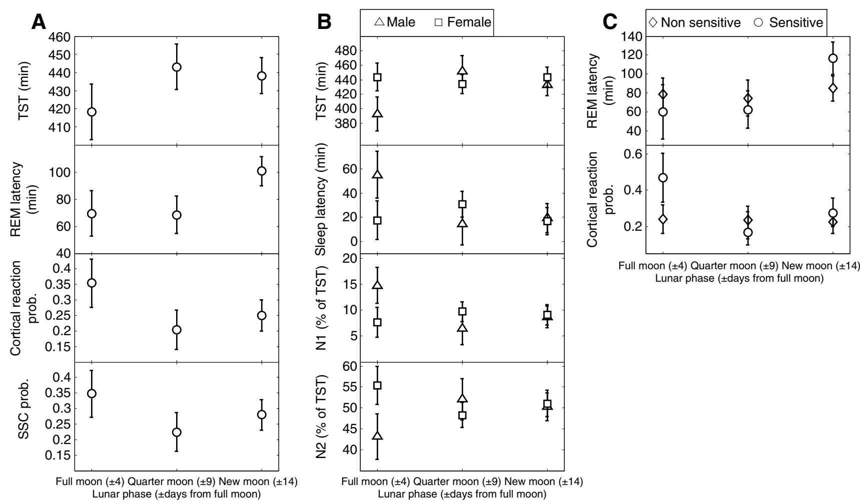

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Figure 1. Effects of lunar cycle on sleep.
(A) Effects of lunar class on total sleep time (TST), and REM latency obtained from quiet control conditions (upper two panes). Effects of lunar class on sleep stage change (SSC) and cortical reaction probabilities obtained from exposure conditions (lower two panes). Significant main effects of lunar class were observed for all. (B) Effects of lunar class on females and males for variables yielding a significant interaction between lunar class and gender. (C) Effects of lunar class on non-sensitive and sensitive groups for variables yielding a significant interaction between lunar class and sensitivity. Error bars indicate 95% confidence intervals.

involved exposing participants to simulated freight rail vibration and noise [5]. Such stimuli are associated with inducing sleep stage changes and cortical reactions (EEG arousals and awakenings), so we examined whether such event-related reactivity is affected by lunar phase. Main effects of lunar class were found for alterations of sleep depth ($F(2,35) = 3.3$, $p = 0.05$) and cortical reactions ($F(2,35) = 4.7$, $p = 0.016$), reflecting increased reactivity around full moon (Figure 1A). However, further analysis of the interaction between sensitivity and lunar phase ($F(2,35) = 3.5$, $p = 0.041$) for cortical reactions reveals that only the sensitive group was more reactive to environmental stimuli around full moon (Figure 1C). Animals with limited nocturnal vision are more readily able to alter hunting behaviors to take advantage of increased light around full moon, and accordingly predators have been found to have higher movement rates around nighttime periods with higher illumination [6]. An increased physiological responsiveness during sleep around such times would allow greater opportunity to react to such predation. Sensitive individuals were classified according to their noise sensitivity, a trait which overlaps with intolerance towards other environmental factors, including light and odorous/pungent chemicals, and is subsequently associated with an increase in overall general sensitivity. Such sensitivity manifests itself in part as heightened attendance to threat [7]. Thus, the increased reaction likelihood of sensitive, i.e. threat-attendant, individuals around full moon supports the notion of the advantage of reaction to predation.

REM latency of sensitive persons did not differ from the non-sensitive group around full or quarter moon, but was 31.7 minutes longer around new moon, suggesting lower REM sleep pressure. Additionally, in our work sensitive individuals had on average 11.2 minutes less SWS than non-sensitive persons. REM sleep pressure and time in SWS has been found to differ between groups with polymorphisms in *period3* (PER3), a gene associated with sleep regulation [8]. Although purely speculative, and taken with earlier suggestions that noise sensitivity has a genetic basis [9], the data hint at possible underlying genetic mechanisms in the regulation of sleep between different population groups.

The existence of endogenous circadian clocks in humans is well documented. In both the present and previous [2] studies, lunar phase was found to impact sleep architecture. It is therefore plausible that an as yet unidentified circalunar clock exists in humans, such as has been demonstrated in marine worms in which the transcript levels of the gene *period* were modulated by the circalunar clock [10]. Future work into such mechanisms is required to gain a deeper understanding of how human sleep is modulated by the phases of the moon.

Supplemental Information

Supplemental Information includes two tables and experimental procedures, and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.05.018.

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